unit

20 C

Photosynthesis and Cellular Respiration

For life to continue on Earth, two conditions must be met. First, matter must be continuously cycled. With few exceptions, the number of atoms on Earth is unchanging. Although the atoms may be rearranged into new molecules, matter is continuously exchanged between plants, animals, fungi, and microorganisms.

The second condition for life on Earth is a supply of energy. Solar energy supplies almost all life on Earth. Plants are the key to keeping the energy flowing. These photo-autotrophs absorb carbon dioxide, water, and radiant energy from the environment and, through photosynthesis, transform these components into energy-rich sugars and oxygen gas. Then, through aerobic respiration, they convert the energy stored in these sugars and oxygen into the energy of ATP.

Heterotrophs, such as animals, fungi, and some protists, obtain nutrients from their environment by eating plants, animals, or both. Like plants, heterotrophs obtain energy in the form of ATP by cellular respiration in which large food molecules are broken down and carbon dioxide and water are returned to the environment. In this unit, you will investigate these transformations and exchanges of energy within our living world.

As you progress through the unit, think about these focusing questions:

- How does light energy from the environment enter living systems?
- How is the energy from light used to synthesize organic matter?
- How is the energy in organic matter released for use by living systems?
- How do humans in their applications of technologies impact photosynthesis and cellular respiration?

UNIT 20 C PERFORMANCE TASK

Student Aquarist

Ecosystems must maintain a delicate balance in order to remain healthy. How do factors such as temperature, light conditions, dissolved oxygen, and dissolved carbon dioxide affect the metabolic health of the organisms within an ecosystem? At the end of this unit, you may apply your skills and knowledge to complete this Performance Task.

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GENERAL OUTCOMES

In this unit, you will

- relate photosynthesis to storage of energy in compounds
- explain the role of cellular respiration in releasing potential energy from organic compounds

Unit 20 C

Photosynthesis and Cellular Respiration

ARE YOU READY?

These questions will help you find out what you already know, and what you need to review, before you continue with this unit.

Prerequisites

Concepts

- organisms, cells, tissues, organ systems
- cellular structures and functions
- passive and active transport of matter

Skills

- use instruments effectively and accurately for collecting data

You can review prerequisite concepts and skills on the Nelson Web site and in the Appendices.

A Unit Pre-Test is also available online.

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Knowledge

1. Match the following names and functions to the labelled components of the cells in **Figure 1** (one name and one function per label).

   Names: *cell membrane, nucleus, vacuole, mitochondrion, endoplasmic reticulum, Golgi apparatus, chloroplast, cell wall, flagellum*

   Functions: *energy conversion, protein storage, protection, material transport within the cell, overall control, food production, water and nutrient storage, controlled entry and exit from cell, locomotion*

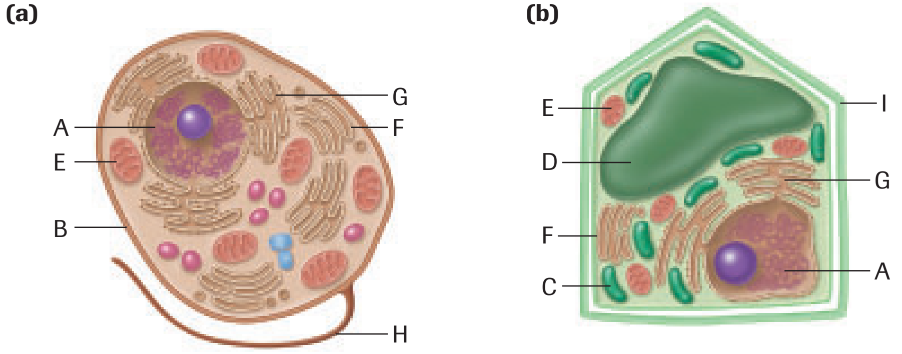

Figure 1
(a) A generalized animal cell; **(b)** A generalized plant cell

2. **Figures 2** and **3** show two processes that move materials into and out of cells.
   (a) What process is represented by **Figure 2**?
   (b) What process is represented by **Figure 3**?
   (c) Name the structure labelled "A" in **Figure 3**.
   (d) What is the substance that passes through structure A in **Figure 3**?

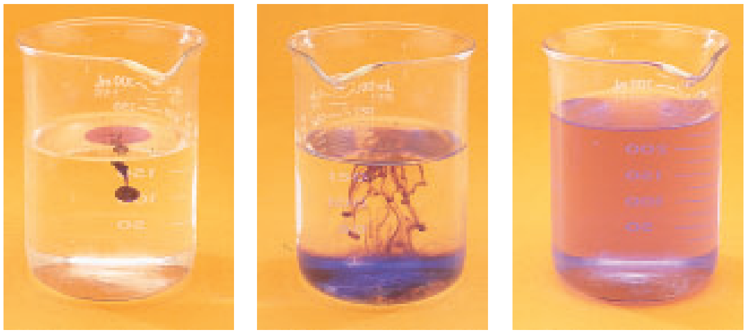

Figure 2

Figure 3

3. Compare passive transport by diffusion and osmosis with active transport in terms of (a) concentration gradients, (b) energy inputs, and (c) equilibrium and protein carrier molecules.

4. Match the following names to the labelled components of the leaf structure in **Figure 4** (one name per label).

   Names: *epidermis, guard cells, palisade tissue, spongy tissue, phloem, xylem, vascular tissue*

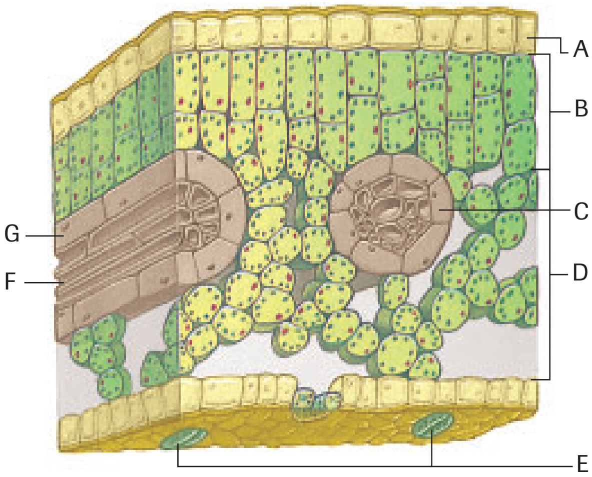

Figure 4
A typical leaf structure

5. **Figure 5** is a wet mount of onion cells viewed under medium power in a compound light microscope.
   (a) What might be the cause of the dark circles in **Figure 5**?
   (b) How could you avoid forming the circles?

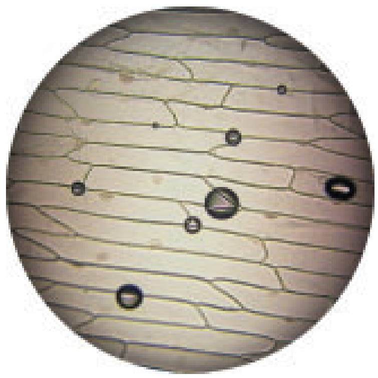

Figure 5
A wet mount of onion cells

Skills

6. Examine the following chemical equation:

CH_4	+	$2\ O_2$	→	CO_2	+	H_2O
methane		oxygen		carbon dioxide		water

   Which of the reactants is a compound? Provide reasons for your answer.

7. Match the following parts of the compound light microscope to the labels in **Figure 6**.

   Microscope parts: *arm, ocular lens, coarse-adjustment knob, stage, fine-adjustment knob, base, condenser, objective lens, revolving nosepiece, stage clips, light source*

8. Place the following steps in the correct order for viewing a slide through a compound light microscope.
   (a) Rotate the nosepiece to the medium-power objective lens.
   (b) Use the fine-adjustment knob to bring the image into focus.
   (c) Place the slide on the stage and hold it in place with clips.
   (d) Use the coarse-adjustment knob to bring the low-power objective lens close to the slide.
   (e) Make sure the low-power objective lens is in place.

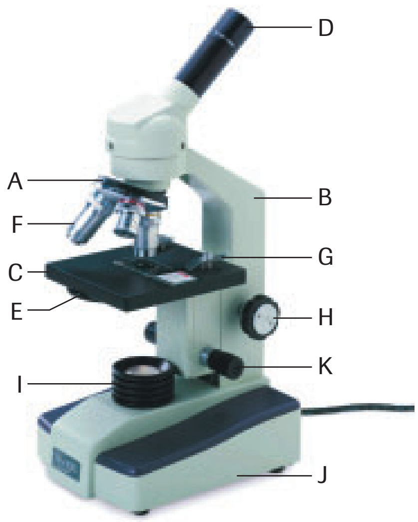

Figure 6
A compound light microscope

chapter

6 Photosynthesis

In this chapter

- Exploration: Global Photosynthesis in Action
- Mini Investigation: Photosynthesis and Light
- Investigation 6.1: Separating Plant Pigments from Leaves
- Case Study: Using Satellite and Airborne Technology to Monitor Photosynthesis and Productivity
- Chemistry Connection: Energy
- Web Activity: Dr. Rudolph Arthur Marcus
- Explore an Issue: Harnessing Light Energy
- Investigation 6.2: How Does Carbon Dioxide Concentration Affect the Rate of Photosynthesis?
- Web Activity: Factors Affecting Photosynthesis
- Career Connection: Nursery Operator

Photosynthesis is the process that converts energy from the Sun into chemical energy that is used by living cells. Photosynthesis occurs in a variety of organisms, but most notably in plants and certain groups of bacteria. The most obvious of these are the large land plants, but the world's oceans are also home to vast quantities of photosynthesizing microorganisms (**Figure 1** on the next page). All of these organisms convert carbon dioxide, $CO_2(g)$, into organic molecules using the light energy captured by chlorophyll.

From a human perspective, photosynthesis is the most important large-scale chemical process on Earth. We are completely dependent on photosynthesis for all the food we eat and the oxygen we breathe. In addition, all organic materials are constructed using the molecular building blocks and the energy supplied by photosynthesis. Therefore, we also rely on photosynthesis for things such as wood, paper, cotton, drugs, and fossil fuels.

As the human population grows and our rates of consumption grow, we become increasingly dependent on vast quantities of photosynthesis products. Recent estimates suggest that humans now consume, either directly or indirectly, close to 40 % of the net primary production of Earth's entire land surface. In other words, over one-third of the yearly production of all of Earth's terrestrial plants is used to meet human demands.

STARTING Points

Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.

1. (a) Write the overall equation for photosynthesis.
(b) Do the O_2 molecules produced in photosynthesis come from CO_2 or H_2O or both?
(c) What is the purpose of water in photosynthesis?

2. Why are deciduous leaves green in the summer and yellow in the fall?

3. What does *carbon fixation* mean?

4. The process of photosynthesis requires energy in the form of ATP. How do plants obtain ATP for photosynthesis?

5. How are the processes of photosynthesis and cellular respiration dependent on each other?

Figure 1
Photosynthesizing organisms live in oceans, lakes, streams, and rivers, as well as on land.

Exploration: Global Photosynthesis in Action

Earth is a dynamic planet of land and water. The seasons are accompanied by changing temperatures and levels of solar radiation—factors that dramatically influence the distribution and activity of photosynthesizing organisms.

Recent technological developments enable us to monitor such changes with great precision. In this Exploration, you will view an animation of biosphere data gathered over six years as part of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project. In the animation, areas of high plant life on land are shown in dark green, while areas of low plant life are shown in tan. In the oceans, areas of high active photosynthesis by phytoplankton are shown in red, and areas of lowest activity are shown in blue and purple (**Figure 2**).

(a) Generate a hypothesis to describe the overall pattern you expect to see on the land surface, and a hypothesis to describe what you expect to see in the oceans. Where and when do you think land plants and marine phytoplankton activity will peak?

(b) After recording your hypotheses, go to the Nelson Web site and follow the links to view the animation sequence.

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(c) Describe the patterns of changes you see over the six-year period.

(d) Note any surprises you observe. Was photosynthesis most active where you expected it to be?

(e) Suggest possible explanations to account for the patterns you witnessed on the land environment and in the marine environment.

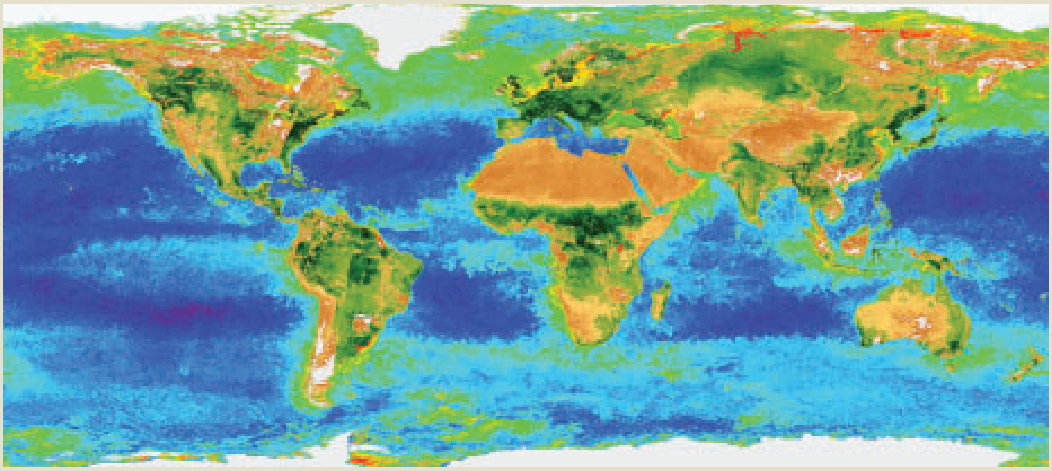

Figure 2
SeaWiFS image of global photosynthesis activity

6.1 Chloroplasts and Photosynthetic Pigments

photon a packet of light

Light is a type of electromagnetic radiation (EMR). Many forms of electromagnetic radiation are familiar to us including X-rays, microwaves, and radio waves. All EMR occurs in the form of individual packets of energy called **photons**. Each photon corresponds to a small unit of energy of a particular wavelength (**Figure 1(a)**). Photons with short wavelengths have high energy and those with long wavelengths have low energy.

Light from the Sun is a mixture of different wavelengths. When passed through a transparent prism in an instrument called a spectroscope, the different wavelengths separate from one another according to their energies, forming the electromagnetic spectrum (**Figure 1(b)**). Most of the spectrum is invisible to humans, being either in the radio, infrared, or ultraviolet range, but a narrow band, from a wavelength of 380 nm (violet light) to 750 nm (red light), forms the visible part of the spectrum.

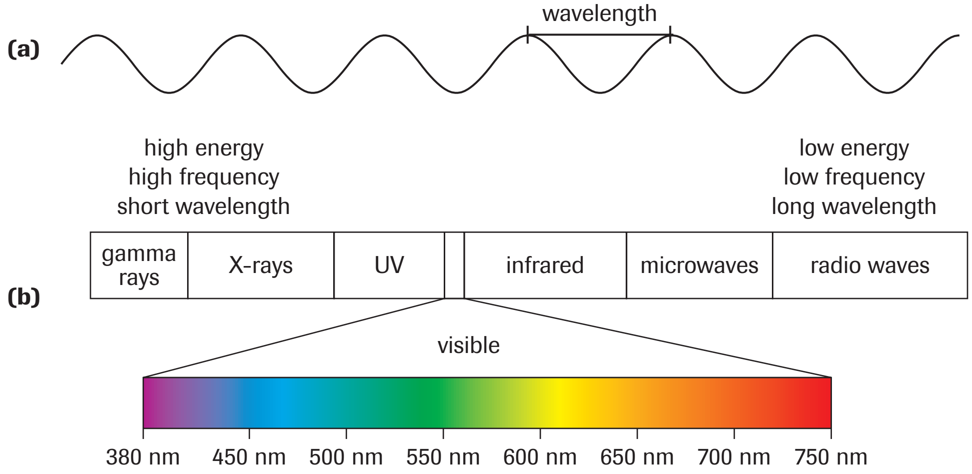

Figure 1
(a) Light is a form of electromagnetic radiation that travels as waves. One wavelength corresponds to a photon.
(b) Light is the visible portion of the electromagnetic radiation spectrum. Our eyes perceive photons of different wavelengths, or energies, as different colours.

CAREER CONNECTION

Nursery Operator

Nursery operators work with plants, growing and selling trees, shrubs, and other plants. They direct and supervise staff to plant, transplant, and feed trees and shrubs, and they also decide the appropriate environmental conditions required to grow particular plants.

Nursery operators often work outdoors on a regular basis, and their work is creative and rewarding. Find out more about this career by visiting the Nelson Web site.

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Solar energy is the ultimate source of energy for most living things. As you saw in Chapter 2, organisms do not use this energy directly. Instead, photosynthetic organisms at the first trophic level in a food web (producers) capture solar energy and then store it as chemical energy in the bonds of glucose molecules. This energy is eventually passed to other organisms in the food web. All organisms, including those that carry out photosynthesis, release the energy in glucose molecules by cellular respiration to fuel cell activities.

Recall that the process of photosynthesis can be summarized by this equation:

$$\begin{array}{ccccccccc} \text{carbon dioxide} & + & \text{water} & + & \text{energy} & \rightarrow & \text{glucose} & + & \text{oxygen} \\ CO_2(g) & + & H_2O(l) & + & \text{energy} & \rightarrow & C_6H_{12}O_6(s) & + & O_2(g) \end{array}$$

This equation includes only the compounds at the beginning and end of the process of photosynthesis. You will learn more about some of the important molecules involved in photosynthesis in the rest of this chapter.

Photosynthesis occurs only in green plants and some photosynthetic micro-organisms such as algae. Special pigments in these organisms capture photons from solar energy to begin the reactions that make up the photosynthesis process.

Practice

1. Name three large groups of organisms that carry out photosynthesis.
2. (a) Define *light*.
   (b) What is a photon?

mini Investigation Photosynthesis and Light

Green plants capture sunlight and transfer the energy to carbohydrates through the process of photosynthesis. When plants photosynthesize, they absorb carbon dioxide and produce oxygen. The oxygen produced is released into the environment. In this activity, you will observe the production of oxygen in photosynthesizing plant cells.

Materials: living green plants with leaves, baking soda, liquid soap or detergent, medicine dropper, water, drinking straw, 35 mm film canister with lid, 5 mL syringe, eye protection

- Add enough baking soda to barely cover the bottom of a film canister. Fill the canister with water (almost to the top), replace the lid, and shake to dissolve the baking soda.
- Remove the lid, add one small drop of liquid soap, replace the lid, and gently swirl the contents to dissolve the soap. Do not shake. The soap will help prevent static electricity.
- Use a new straw like a cookie-cutter to cut four leaf discs from a plant leaf. The leaf discs will accumulate inside the straw.

Never share straws with others. Always use a new straw. When finished using the straw, discard it in the garbage can.

- If the syringe you are using has a cap on the tip, remove the cap. Pull the plunger out of the syringe. Blow the leaf discs out of the straw and into the syringe. Replace the plunger.
- Draw 4 mL of baking-soda solution (prepared in the first two steps) into the syringe. Invert the syringe so that the tip end is pointing up. Gently push the plunger to remove the air near the tip.
- Put your finger over the syringe tip and pull the plunger. This will create a vacuum, which will pull air and oxygen from the leaf discs (**Figure 2**).

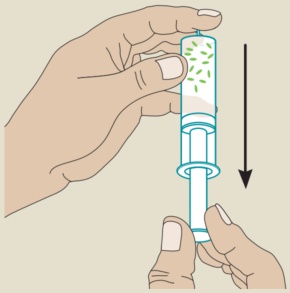

Figure 2

- Tip the end of the syringe down so that the leaf discs are in the solution. Release the plunger and remove your finger. Turn the syringe back up and tap the side repeatedly until all (or most) of the discs sink.
- Place the syringe, open end up, in bright sunlight.
- As the leaf discs photosynthesize, they will float to the top.

(a) (i) What causes the leaf discs to float to the top while they are in sunlight?
    (ii) Would the discs float to the top if the syringe was kept in the dark? Explain.
(b) Why is baking soda added to the solution in the syringe?
(c) Did the leaf discs all float to the top at the same time? Explain why or why not.
(d) How could this procedure be used to investigate whether or not different colours of light cause plants to photosynthesize equally well? Design a procedure for such an experiment (include a list of materials).

Chlorophyll

Photosynthesis is carried out by a number of different organisms, including plants, algae, some protists, and cyanobacteria. These organisms all contain the green-coloured pigment called **chlorophyll**. Chlorophyll absorbs photons from solar energy and begins the process of photosynthesis. Several types of chlorophyll are found in photosynthetic organisms; chlorophyll *a* (blue-green) and chlorophyll *b* (yellow-green) are two common forms. All photosynthetic organisms use chlorophyll *a* as the primary light-absorbing pigment.

chlorophyll the light-absorbing green-coloured pigment that begins the process of photosynthesis

Chlorophylls *a* and *b* absorb photons with energies in the blue-violet and red regions of the spectrum and reflect or transmit those with wavelengths between about 500 nm and 600 nm, which our eyes see as green light. This is why most photosynthesizing organisms look green in white light. Using a sophisticated instrument called a

EXTENSION

The Action Spectrum, the Absorption Spectrum, and Photosynthesis

Listen to this Audio Clip, which explores absorption and action spectra for the primary photosynthetic pigments chlorophyll *a* and *b*.

spectrophotometer, the absorption spectrum of pigments, such as chlorophyll *a* and chlorophyll *b*, can be determined with accuracy, as **Figure 3** shows.

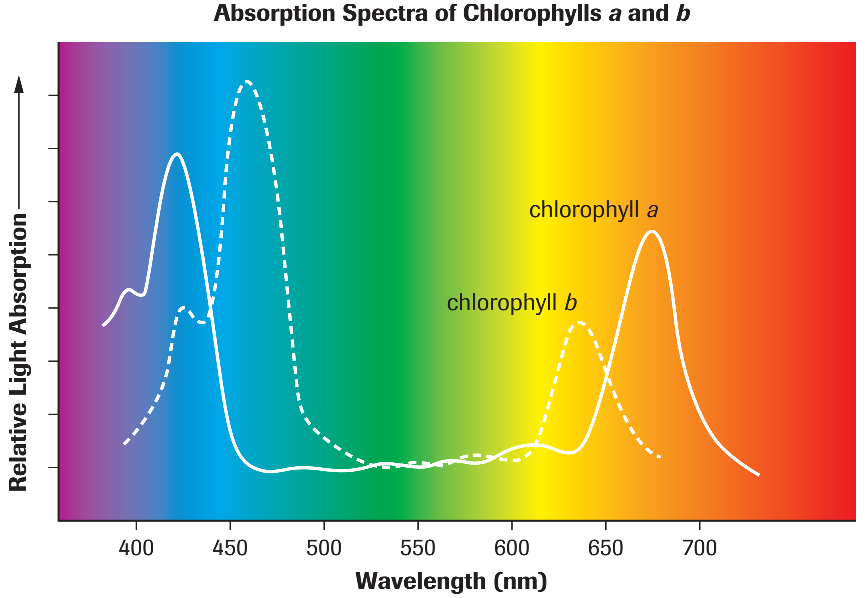

Figure 3
The absorption spectrum of chlorophyll *a* and chlorophyll *b*.

Chlorophyll *a* is the only pigment that can transfer the energy from sunlight to the reactions of photosynthesis. Chlorophyll *b* acts as an accessory pigment, absorbing photons that chlorophyll *a* absorbs poorly, or not at all. Other compounds, called carotenoids, also act as accessory pigments. These and other accessory pigments usually transfer the energy they absorb back to a molecule of chlorophyll *a*.

In spring and summer, most leaves appear green because of the high concentration of chlorophyll in the chloroplasts of leaf cells. Although the accessory pigments are also present, their colours are overwhelmed by the green light reflected by chlorophyll. With the onset of cooler autumn temperatures, plants stop producing chlorophyll molecules and disassemble those already in the leaves. This causes the yellow, red, and brown colours of autumn leaves to become visible, as **Figure 4** shows.

Figure 4
Autumn leaves contain less chlorophyll, so the colours of the accessory and other pigments can be seen.

Practice

3. What is the primary light absorbing pigment in all photosynthetic organisms?

4. What colour(s) of the spectrum is absorbed by chlorophyll *a* and chlorophyll *b*? What colour(s) is transmitted by these pigments?

INVESTIGATION 6.1 *Introduction*

Separating Plant Pigments from Leaves

Look at **Figure 5** with unaided eyes and determine its colour. Now look at the figure with a magnifying glass. What colours do you see? The spring and summer leaves of deciduous trees appear green in colour. Do green leaves contain only green pigments, or is there a mixture of pigments with the green variety predominating? Investigation 6.1 will help you decide.

To perform this investigation, turn to page 195.

Report Checklist

● Purpose	○ Design	● Analysis
● Problem	○ Materials	● Evaluation
○ Hypothesis	○ Procedure	○ Synthesis
● Prediction	● Evidence	

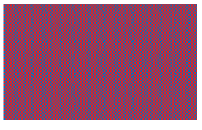

Figure 5
A colour made up of other colours.

Chloroplasts

Leaves are the primary photosynthetic organs of most plants. To undergo photosynthesis, a plant cell must contain chlorophyll, and it must be able to obtain carbon dioxide and water, and capture solar energy from its environment. Plant cells contain chloropyll within the photosynthetic membranes of discrete organelles called **chloroplasts**. Because they contain chlorophyll, chloroplasts give leaves, stems, and unripened fruit their characteristic green colour. Since chloroplasts are found only in these parts, no other structures in a plant are able to photosynthesize.

A typical plant cell chloroplast is approximately 3 μm to 8 μm in length and 2 μm to 3 μm in diameter. Chloroplasts have two limiting membranes, an outer membrane and an inner membrane (**Figure 6**). These membranes enclose an interior space filled with a protein-rich semiliquid material called **stroma**. Within the stroma, a system of membrane-bound sacs called **thylakoids** stack on top of one another to form characteristic columns called **grana**. A typical chloroplast has approximately 60 grana, each consisting of 30 to 50 thylakoids. Adjacent grana are connected to one another by unstacked thylakoids called **lamellae**. Photosynthesis occurs partly within the stroma and partly within the **thylakoid membrane**, which contains light-gathering pigment molecules and other molecules and complexes that are essential to the process. Thylakoid membranes enclose an interior (water-filled) thylakoid space called the **thylakoid lumen**. The structure of the thylakoid system within the chloroplast greatly increases the surface area of the thylakoid membrane and, therefore, also significantly increases the efficiency of photosynthesis. Chloroplasts are able to replicate, by division, independently of the cell. Starch grains and lipid droplets may also be found in chloroplasts.

chloroplast a membrane-bound organelle in green plant and algal cells that carries out photosynthesis

stroma the protein-rich semiliquid material in the interior of a chloroplast

thylakoid a system of interconnected flattened membrane sacs forming a separate compartment within the stroma of a chloroplast

grana (singular: *granum*) stacks of thylakoids

lamellae (singular: *lamella*) groups of unstacked thylakoids between grana

thylakoid membrane the photosynthetic membrane within a chloroplast that contains light-gathering pigment molecules and electron transport chains

thylakoid lumen the fluid-filled space inside a thylakoid

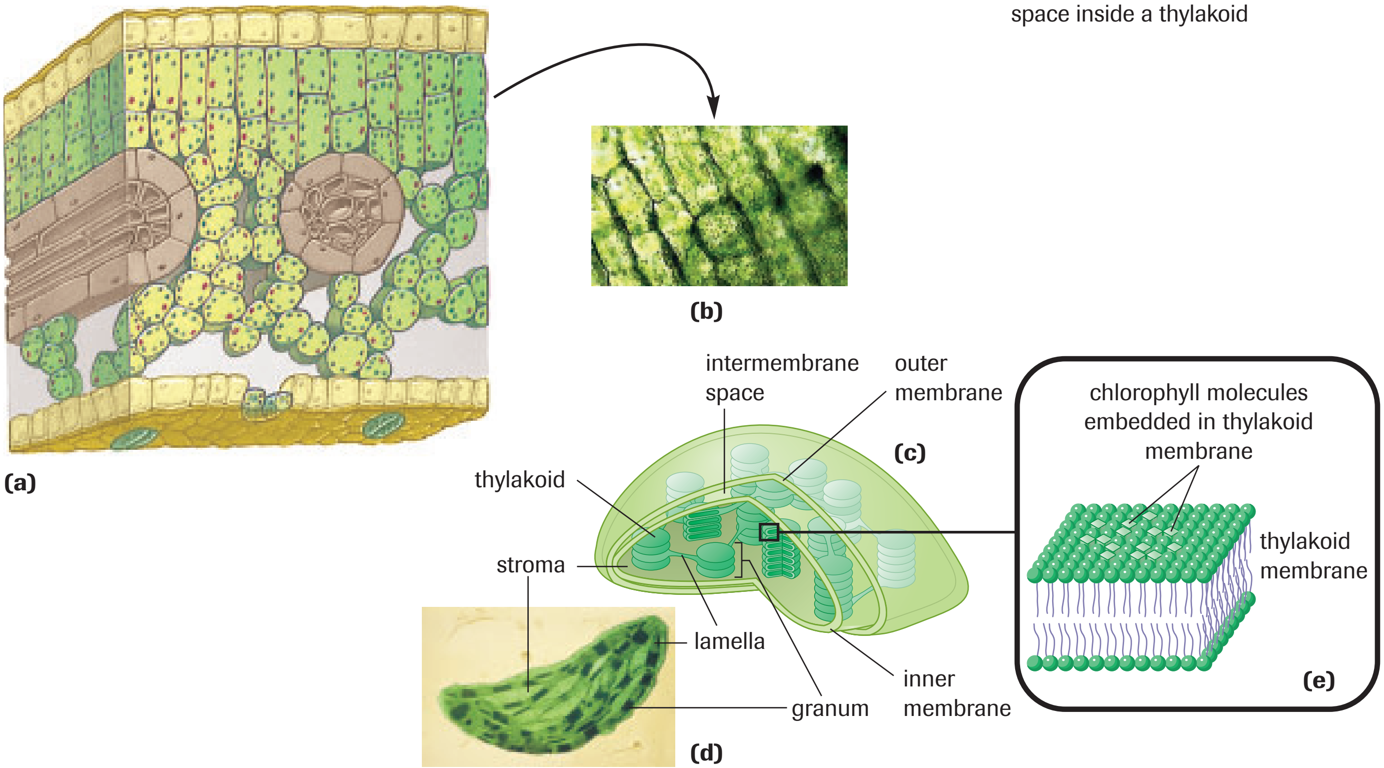

Figure 6
(a) Leaf cross section with mesophyll cells containing chloroplasts
(b) Chloroplasts within plant cells
(c) An artist's representation of a chloroplast, showing key components
(d) An electron micrograph of a chloroplast
(e) Chlorophyll molecules in the thylakoid membrane

Case Study

Using Satellite and Airborne Technology to Monitor Photosynthesis and Productivity

Healthy crop plants generally have a high chlorophyll content and a normal leaf structure. The leaves reflect green and infrared light and a small amount of red light—the red light is readily absorbed by higher concentrations of chlorophyll. In contrast, stressed or damaged plants have a lower chlorophyll content and an altered leaf structure. These changes reduce the amount of green and infrared light that is reflected. The ratio of reflected infrared light to reflected red light is an excellent indicator of plant health, and changes in this ratio are an early indication of stress conditions. These ratios form the basis of some standards, or health indexes, such as the normalized differential vegetation index (NDVI).

Farmers can assess stresses within fields using this same technology. The airborne image of fields near Altona, Manitoba (**Figure 7**) can be used in a variety of ways. The more deeply coloured red (wheat) and pink (canola) regions are healthy while the darker and duller regions have thin or missing vegetation. This image was obtained using a compact airborne spectrographic imager (CASI) instrument.

Deforestation is a global problem, with many serious consequences. In tropical countries, valuable rain forest is being destroyed to clear potentially valuable agricultural and pasture land. The loss of forests increases soil erosion, damages or destroys fisheries and wildlife habitat, and threatens water supplies. In some countries, such as Haiti, the results have been devastating, with most of the land base now completely devoid of crops or forests. Forestry is one of Canada's biggest industries and proper forest management is essential for a healthy, strong, sustainable economy. Remote sensing technology provides the best way to monitor the overall extent and health of our forest resources.

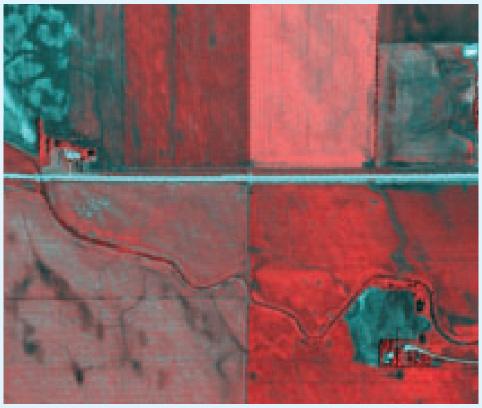

Figure 7
Remote sensing technology can provide valuable information to assess field crop health. The dark patches in the lower-left corner reveal poorly drained soil.

Clear cutting has been practised for decades in Whitecourt, Alberta. Recently however, an increasing demand for wood has accelerated this cutting and placed added stress on the land base (**Figure 8**). In addition to harvesting for the forestry industry, cuts have been made in the area for running seismic lines for oil and gas exploration.

Figure 8
This image of clear cutting near Whitecourt, Alberta reveals a highly dissected forest.

Case Study Questions

1. What symptoms of plant stress can be used to advantage by remote sensing technologies?
2. Suggest a reason why healthy plants reflect less light from the red end of the spectrum than plants under stress.
3. What ratio is used in the NDVI?
4. List some of the potentially negative consequences of excessive clear cutting. Why might Canadians be particularly concerned about the health of our forest ecosystems?
5. What advantages might the use of remote monitoring of forest management practices have over on-the-ground inspections?
6. Why are different sensor technologies often used to monitor clear cutting in tropical rain forests and temperate forests?
7. How have Aboriginal people living on First Nations and Métis Settlement lands in Alberta benefited from their forest reserves?
8. Investigate clear-cutting activities on First Nations lands such as the Morley First Nation in southern Alberta during the 90s. Report on your findings by creating a pamphlet.

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SUMMARY Chloroplasts and Photosynthetic Pigments

- Light is a form of energy that travels in the form of photons.
- Chlorophyll *a* is the only pigment that can transfer the energy of light to the carbon fixation reactions of photosynthesis. Chlorophyll *b* and the carotenoids act as accessory pigments, transferring their energy to chlorophyll *a*.
- Chloroplasts have an outer membrane and an inner membrane. The interior space contains a semiliquid material called stroma with a system of membrane-bound sacs called thylakoids, some of which are stacked on top of one another to form grana. Thylakoid membranes contain chlorophyll molecules and electron transport chains.

EXTENSION

Action Spectrum

In this Virtual Biology Lab, you will measure which wavelengths of light are most effective for photosynthesis.

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Section 6.1 Questions

1. (a) How are the wavelength and energy of a photon related?
   (b) Which possesses a higher energy value: red light or green light? Explain.
   (c) How is the colour of light related to its energy? Provide examples.
2. (a) What pigments are present in green leaves?
   (b) Explain why yellow-coloured pigments are visible in autumn leaves but not in summer leaves.
3. What do all photosynthetic organisms have in common?
4. Label parts A, B, C, and D of the chloroplast in **Figure 9**.

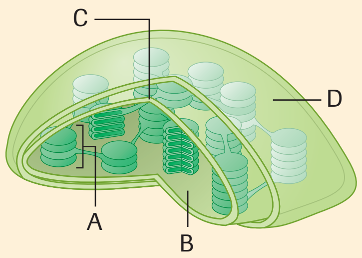

Figure 9
A chloroplast

5. Many lightbulb manufacturers produce fluorescent tubes labelled as “growlights” that they claim emit “full-spectrum light that imitates sunlight.” Conduct research to determine whether fluorescent tubes labelled as “growlights” are more effective sources of artificial light for growing plants indoors than tubes without this label.

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6. Several biotechnology companies are experimenting with the possibility of producing a “green” (environmentally friendly) plastic from plants. One procedure converts sugar from corn to polylactide, a plastic similar to the plastic polyethylene terephthalate, which is used to make pop bottles and a variety of synthetic fabrics. Conduct research to complete the following tasks:
   (a) Describe one or two other “green” plastics and their potential uses.
   (b) Describe some of the costs and benefits of producing “green” products on a large scale.

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7. Recent advances in remote sensing have made detection of plant health possible on a large scale. Using satellite images, spectral analysis, and other sensing technologies, farmers may now detect problems in large fields of crops before they are identified at ground level. Conduct library and/or Internet research about spectral remote sensing as applied to plants to answer the following questions:
   (a) What characteristic(s) of plants do remote sensing systems detect to provide information regarding a crop’s overall health?
   (b) Why would a farmer spend money to have crops tested by these methods? What advantages are gained by the procedure?
   (c) Describe the strategy or strategies you used to conduct your Internet search. List the advantages and disadvantages of each strategy.

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6.2 The Reactions of Photosynthesis

As you have learned, chlorophyll and other pigments located within the chloroplasts of green plants capture packages of energy called photons from sunlight. During photosynthesis, this captured energy is converted into chemical energy in the bonds of glucose molecules. Each molecule of glucose is synthesized from six molecules of carbon dioxide and six molecules of water.

Photosynthesis is a process made up of a series of complex chemical reactions that form a variety of intermediate and final energy-rich molecules. These molecules serve a number of different energy-related functions within cells (**Table 1**).

+ EXTENSION

A Brief History of Photosynthesis Research
Our current understanding of photosynthesis is constructed from the work of many scientists from the 1600s onward, and the work continues today. Read about some of the classic experiments in photosynthesis research and complete the questions to assess your understanding.

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Table 1 Energy-Containing Molecules Formed during Photosynthesis

Molecule	Function
ATP	• principal energy-supply molecule for cellular functions of all living cells • provides an immediate source of energy for cellular processes, such as growth and movement
NADPH	• electron donor (NADPH) involved in energy transfers
glucose	• transport molecule ("blood sugar") • medium-term energy storage in most cells

ATP a molecule containing three high-energy phosphate bonds that acts as the primary energy-transferring molecule in living organisms

ADP a molecule containing two high-energy phosphate bonds that may be formed by breaking one of the phosphate bonds in ATP

Glucose is used to store energy for later use by cells. However, of all the energy-rich molecules in living cells, none is more significant than **ATP** (adenosine triphosphate). ATP is used by all living cells, both plant and animal, to provide immediate energy for cellular functions, such as synthesis of needed chemicals and transport of materials across cell membranes. ATP is formed by the addition of an inorganic phosphate group (P_i) to a molecule of lower-energy **ADP** (adenosine diphosphate). Later, this same energy can be released to the cell by a chemical reaction that splits ATP back into ADP and P_i (**Figure 1**).

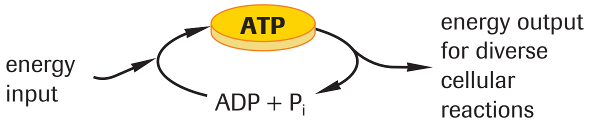

Figure 1
Energy is stored when ATP is formed from a phosphate group and ADP. This energy can be released when needed by the reversal of this reaction.

$NADP^+$ a compound that accepts one hydrogen atom and two electrons, forming NADPH; is an electron acceptor

NADPH a compound that donates one hydrogen atom and two electrons to another molecule, to reform $NADP^+$; is an electron donor

The compound **$NADP^+$** (nicotinamide dinucleotide phosphate) may also participate in many cellular reactions. At several places during photosynthesis, $NADP^+$ accepts one hydrogen atom and two electrons to form **NADPH**. NADPH may then donate electrons to other molecules in the cell, and so becomes $NADP^+$ again. In the rest of this section, you will find out how the gain and loss of electrons from $NADP^+$ and NADPH contributes to the process of photosynthesis.

An Overview of Photosynthesis

As you have learned, chlorophyll molecules and other pigments located within chloroplasts are able to absorb solar energy. To be useful to the plant, this solar energy must be converted to chemical energy. Once the energy is in a chemical form, it can be transported throughout the cell and to other parts of the plant, and it can also be stored.

The pigments and chemicals involved in these pathways are arranged within the chloroplast to make these tasks operate efficiently. While these physical arrangements and chemical pathways are complex and involve many intermediate steps, the overall process is relatively straightforward and can be broken down into the following three distinct, but connected, stages.

Stage 1: *capturing solar energy and transferring it to electrons*

Stage 2: *using captured solar energy to make ATP and to transfer high-energy electrons to* $NADP^+$*; yields NADPH, which is then used as a high-energy electron carrier molecule*

Stage 3: *using energy stored in ATP and high-energy electrons carried by NADPH to form energy-rich organic molecules, such as glucose, from* CO_2

The first two stages involve a series of reactions that are directly energized by light, called the **light-dependent reactions**. These reactions require chlorophyll and occur on the thylakoid membranes in chloroplasts. Chlorophyll absorbs the light energy that is eventually transferred to carbohydrate molecules in the last stage of the process. The reactions of the third stage result in **carbon fixation**—the incorporation of the carbon of $CO_2(g)$ into organic compounds, such as glucose. These reactions take place in the stroma of the chloroplast and utilize the energy of ATP and high energy electrons carried by NADPH. Carbon fixation takes place in the stroma by means of a cyclic sequence of enzyme-catalyzed reactions called the **Calvin cycle** (Figure 2). The reactions of the Calvin cycle are **light-independent reactions**.

light-dependent reactions the first set of reactions of photosynthesis in which light energy excites electrons in chlorophyll molecules, powers chemiosmotic ATP synthesis, and results in the reduction of $NADP^+$ to NADPH

carbon fixation the process of incorporating CO_2 into carbohydrate molecules

Calvin cycle a cyclic set of reactions occurring in the stroma of chloroplasts that fixes the carbon of CO_2 into carbohydrate molecules and recycles coenzymes

light-independent reactions the second set of reactions in photosynthesis (the Calvin cycle); these reactions do not require solar energy

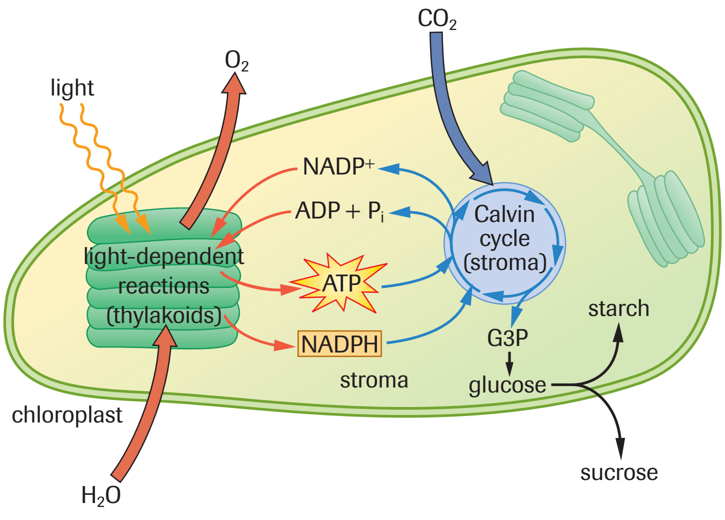

Figure 2
An overview of photosynthesis. The light-dependent reactions of photosynthesis occur in the thylakoid membranes of chloroplasts and transfer the energy of light to ATP and NADPH. The Calvin cycle takes place in the stroma and uses NADPH to reduce CO_2 to organic compounds, such as glucose and other carbohydrates.

Practice

1. Name three energy-containing molecules that are formed during photosynthesis.
2. Where do the light-dependent reactions of photosynthesis take place?
3. Where does carbon fixation take place?

Stage 1: Capturing Solar Energy

Within the chloroplasts, chlorophyll and other pigment molecules are found in clusters embedded in the thylakoid membranes. These molecule arrangements are called **photosystems**. As you will soon see, the light-dependent reactions rely on two distinct but interconnected photosystems—photosystems I and II—numbered in order of their discovery. These molecules are responsible for the actual capturing of light energy.

photosystem a cluster of photosynthetic pigments embedded in a thylakoid membrane of a chloroplast that absorbs light energy

Solar energy is captured when an electron in a chlorophyll molecule (or in another pigment molecule) absorbs a photon. Electrons are high-energy particles present in all atoms. Before a photon of light strikes, the electron has a relatively low amount of energy. After the photon is absorbed, the electron has a relatively high amount of energy, and is said to be excited. The photon has now been converted to chemical energy!

Still in the thylakoid membrane, the excited electron is then removed from the photosystem and passed from one molecular complex to another in a long series of steps often referred to as an **electron transport chain**.

electron transport chain a series of progressively stronger electron acceptors; each time an electron is transferred, energy is released

The electrons that are being removed from each photosystem to enter the electron transport chain must be replaced. These replacement electrons come from water molecules, in a process call photolysis. In **photolysis**, the solar energy absorbed by the chlorophyll is used to split water into hydrogen ions (H^+) and oxygen gas. Photolysis occurs in the thylakoid lumen.

photolysis a chemical reaction in which a compound is broken down by light; in photosynthesis, water molecules are split by photolysis

Two water molecules are consumed for every four electrons transferred to a photosystem.

$$2\ H_2O(l) + \text{energy} \rightarrow 4\ H^+ + 4\ e^- + O_2(g)$$

EXTENSION

Is Light Necessary for Photosynthesis?
Plants seem to need light to stay alive. In this activity, you will analyze leaves exposed to sunlight and leaves "starved" of sunlight to determine whether leaves need light to produce starch, a molecule made from glucose.

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Practice

4. Where are photosystems I and II located?
5. What happens when chlorophyll absorbs a photon?
6. How are the electrons that are passed on to the electron transport chain replaced?

Stage 2: Electron Transfer and ATP Synthesis

The solar energy captured by the pigments within photosystems must now be used to form additional stable energy-rich molecules and to make ATP from ADP and P_i. These tasks are performed by two distinctly different mechanisms—one involving the buildup of charged particles and the other involving the direct transfer of electrons.

The Electron Transport Chain

Both of these mechanisms depend on the electron transport chain. In many ways, the electron transport chain is similar to the set of stairs shown in **Figure 3** on the next page. Solar energy is used to excite electrons that have been removed from a water molecule. This added energy lifts them up in a single leap to the top of the energy stairway (the electron transport chain). This potential energy is then gradually released as the electrons travel down the stairs to their original lower energy level. Some of this released energy is captured to make ATP. The electrons eventually rejoin H^+ ions in the formation of new compounds.

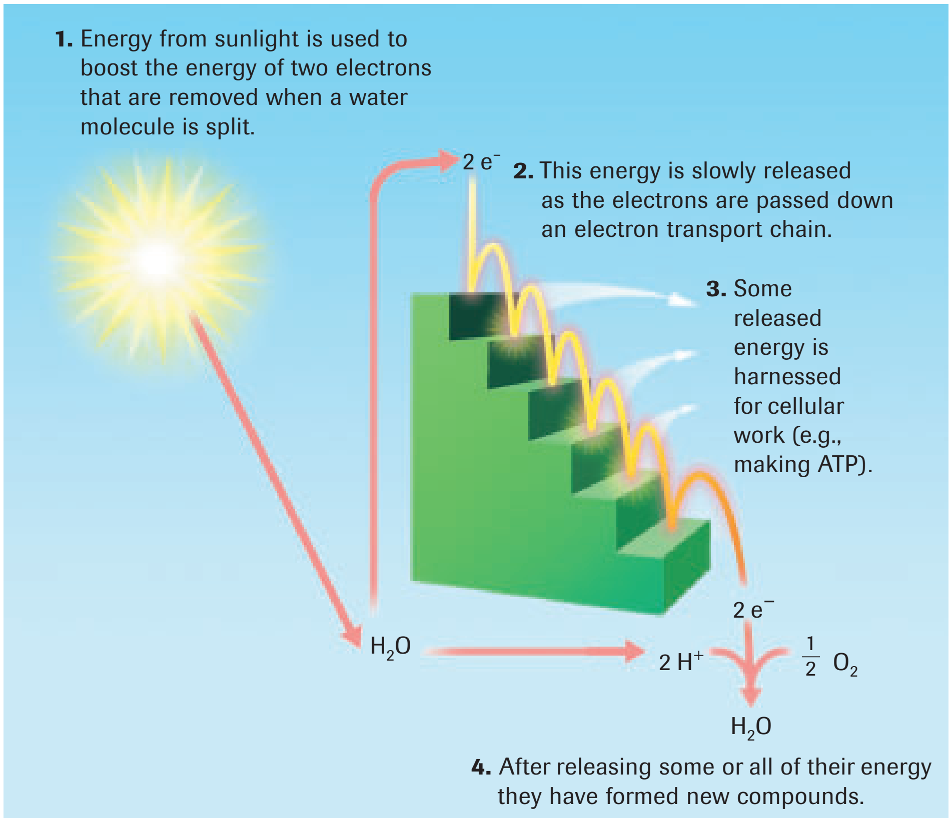

Figure 3
The step-by-step release of energy by electron transport chains enables cells to release energy in smaller, usable amounts.

Oxidation–Reduction Reactions

How does the transfer of electrons release energy? At each step in the electron transport chain, a higher-energy electron donor passes an electron to a lower-energy electron acceptor. Such reactions are called oxidation–reduction or redox reactions. An **oxidation** is a reaction in which an atom or molecule loses electrons. A **reduction** is a reaction in which an atom or molecule gains electrons. An electron transfer between two substances always involves both an oxidation and a reduction.

Electron donors, such as NADPH (an electron carrier in the electron transport chain in chloroplasts), tend to lose electrons. Electron acceptors, such as $NADP^+$, tend to gain electrons. When NADPH is oxidized, it loses a hydrogen nucleus (H^+) and its two electrons ($2\ e^-$), and is converted to $NADP^+$. When $NADP^+$ is reduced, it gains a hydrogen nucleus and its two electrons, and is converted to NADPH. When an element or molecule gains electrons (is reduced), it releases energy and becomes more stable. Therefore, whenever $NADP^+$ is converted to NADPH, energy is released. NADPH then donates electrons to other molecules for other processes in the cell, such as in the dark reactions of photosynthesis (Stage 3).

CHEMISTRY CONNECTION

Energy
There are two classes of energy: potential energy and kinetic energy. In simple terms, potential energy is stored energy and kinetic energy is the energy of motion. The energy captured in photosynthesis is potential energy. Your chemistry textbook contains more information on the types of energy.

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oxidation a reaction in which an atom or molecule loses electrons

reduction a reaction in which an atom or molecule gains electrons

Learning Tip

Remember: LEO goes GER.
Loss of Electrons is Oxidation;
Gain of Electrons is Reduction

Practice

7. What happens to the electrons that are released during photolysis?
8. What is the role of electron donors and electron acceptors in the steps of the electron transport chain?
9. What is an oxidation? What is a reduction?
10. What is the role of oxidations and reductions in the electron transport chain?

EXTENSION

Electron Transport in the Thylakoid Membrane
Listen to this Audio Clip for information on how changes in the energy levels of electrons allow plants to capture and transform light energy into chemical energy through the process of photosynthesis.

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Let's now follow the pathway of other electrons that were first excited by light in photosystem II (**Figure 4**). As the electrons are passed along an electron transport chain from one chemical complex to another, they are also carried across the thylakoid membrane—from the outer surface—toward the thylakoid lumen, as seen in (**A**). In doing so, they release energy, which is used to "pull" a number of positively charged hydrogen ions

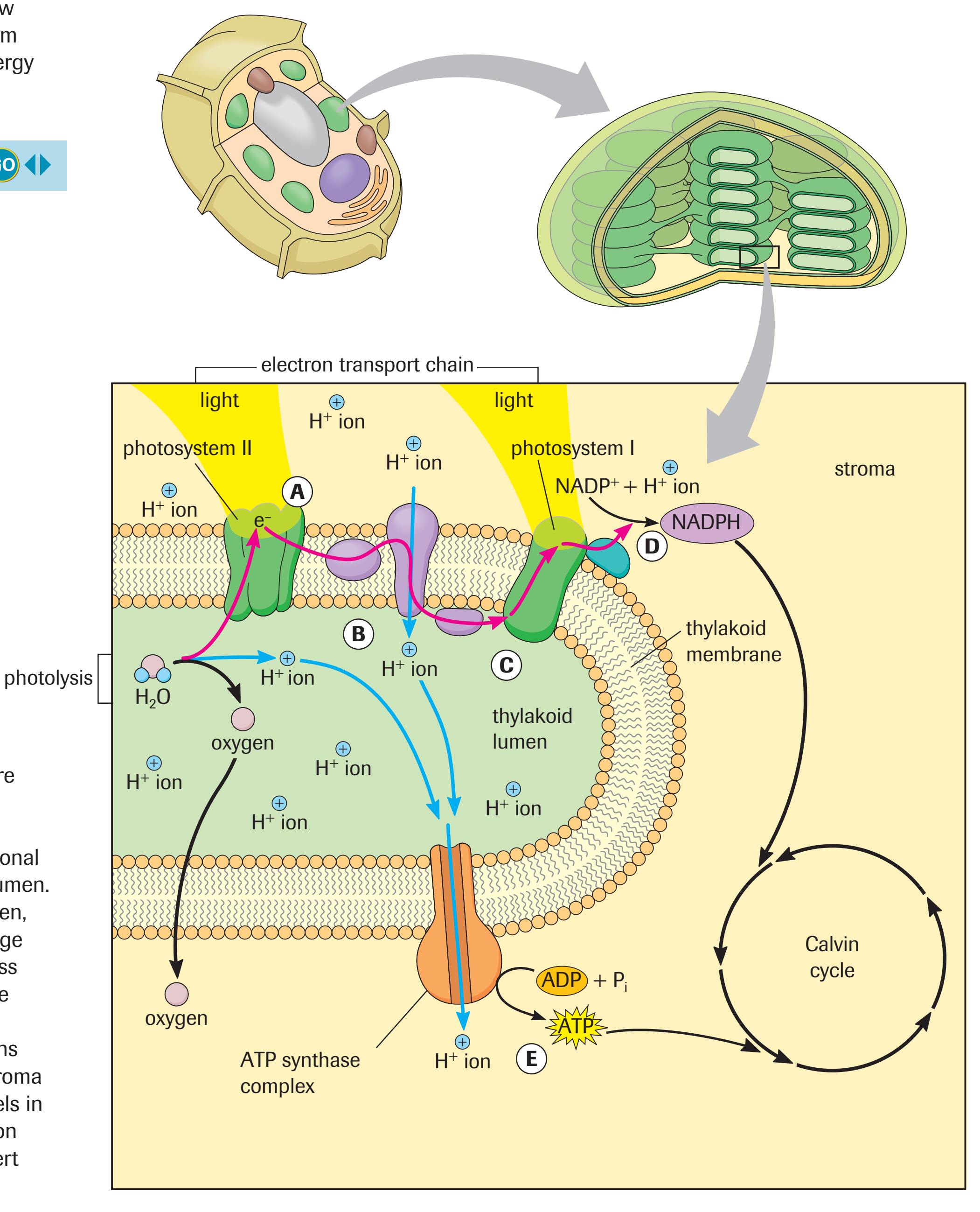

Figure 4
H^+ ions are released into the thylakoid lumen as electrons are removed from water. As these electrons are passed along an electron transport chain, additional H^+ ions are pumped into the lumen. H^+ ions accumulate in the lumen, increasing the gradient of charge and H^+ ion concentration across the thylakoid membrane. As the concentration and electrical gradients begin to build, H^+ ions move from the lumen to the stroma through special protein channels in the thylakoid membrane. The ion flow drives enzymes that convert ADP and P_i into ATP.

(H^+) across the membrane into the lumen (**B**). The electrons have now lost much of the energy that they received from light in photosystem II. However, their journey is not over. As H^+ ions are continuously pulled across the thylakoid membrane, their concentration increases inside the lumen and a positive charge begins to build up.

After moving to the inside of the thylakoid membrane, the electrons are transferred to a second photosystem—photosystem I (**C**). Here, they replace electrons that are energized by light. The electrons that are energized in photosystem I, unlike those in photosystem II, are not passed across the thylakoid membrane. Instead, they are transferred via a series of chemical complexes to $NADP^+$ (**D**). Each $NADP^+$ is able to accept two high-energy electrons and an H^+ ion from the surroundings as it changes to NADPH. The NADPH molecules formed in this process are used to transfer high-energy electrons to the Calvin cycle in Stage 3.

Key steps in electron transfer during the light-dependent reactions of photosynthesis are:

1. Electrons from photosystem II are transferred along an electron transport chain and across the thylakoid membrane to the inner surface.
2. Some of their energy is used to pull H^+ ions across the membrane, resulting in a buildup of positive charge within the lumen.
3. The electrons, having lost much of their original energy, are then transferred to chlorophyll molecules in the photosystem I complex, where they again absorb solar energy and reach an excited state.
4. High-energy electrons from photosystem I are transferred to $NADP^+$ to form NADPH.

DID YOU KNOW?

The Cost of Chlorophyll

Leaves from shade-tolerant plants have more chlorophyll per photosystem than leaves from light-loving plants. This added cost is necessary to ensure enough light is captured for photosynthesis.

Chemiosmosis

Recall the H^+ ions that were pulled across the thylakoid membrane by the first electron transport chain at position (**B**). This process results in increasing concentration and electrical gradients across the thylakoid membrane. These gradients can now be put to good use. The H^+ ions are unable to escape from the lumen except through specialized protein complexes embedded in the membrane, named **ATP synthase complexes**. As the H^+ ions rush through these complexes, they release energy. The complexes are able to use some of the energy released by H^+ ions to combine ADP with P_i. The process of making ATP using the energy from an H^+ ion gradient is called **chemiosmosis**. Note that the energy stored in the H^+ ion gradient is derived from the energy of the electrons energized by photosystem II. As a result, it can be stated that the energy used by the plant to make ATP originally comes from sunlight.

Overall, the light-dependent reactions consume water and result in the formation of ATP, NADPH, and oxygen. ATP and NADPH play a critical role in the next phase of photosynthesis: carbon fixation.

ATP synthase complex a specialized protein complex embedded in the thylakoid membrane that allows H^+ ions to escape from the lumen and uses the resulting energy to generate ATP

chemiosmosis a process for synthesizing ATP using the energy of an electrochemical gradient and the ATP synthase enzyme

Practice

11. Where does the energy used to pull H^+ into the thylakoid lumen come from?
12. What are the H^+ ions that are pulled inside the thylakoid membranes used for?
13. Why is the production of NADPH important?
14. What is chemiosmosis?

Figure 5
Dr. Rudolph Arthur Marcus

WEB Activity

Canadian Achiever—Dr. Rudolph Arthur Marcus

The formation of ATP during photosynthesis depends on the transfer of electrons. Dr. Marcus (**Figure 5**), born and educated in Montreal, Quebec, was a main contributor to the development of this idea. From 1956 to 1964, he published a number of papers on what is now called the Marcus theory of electron transfer reactions. The Marcus theory also explained other phenomena that are very different from photosynthesis. Find out more about the life and work of Marcus, and then explain how his work contributed to our understanding of photosynthesis.

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EXPLORE an issue

Harnessing Light Energy

Issue Checklist

- ● Issue
- ○ Design
- ● Analysis
- ● Resolution
- ● Evidence
- ● Evaluation

By utilizing sunlight, plants produce food through photosynthesis. When we use plants for food, we are using photosynthesis to meet our basic biological energy demands. Photosynthesis also supplies the wood we use as fuel, and was even responsible for producing the fossil fuels we use today. However, with an ever-increasing demand for abundant, environmentally friendly energy supplies, scientists are researching and refining artificial technologies for capturing and utilizing light energy.

Photosynthesis converts light energy directly into chemical energy. However, the most widely used solar technologies to date convert solar energy into heat (solar collectors such as rooftop solar hot-water heaters) or electrical energy (solar (photovoltaic) cells).

Recently, scientists have started to investigate mimicking photosynthesis by using chemical processes to create artificial photosynthetic systems. Some researchers believe that such artificial photosynthetic technology holds great promise. Some scientists are researching how to directly harness solar energy in the form of ATP, while others are attempting to mimic the carbon fixation reactions in the Calvin cycle. One research team is designing and using artificial catalysts that are able to use solar energy to convert CO_2 to CO—the first stage in the fixation of carbon. This could lead to the production of inexpensive fuels such as methanol and raw materials for the chemical industry.

How do these three technological approaches: converting solar energy into heat energy, electrical energy, and chemical energy compare to the efficiency of plant photosynthesis? What are the advantages and disadvantages of each method as a source of clean energy?

1. Conduct library and/or Internet research to investigate current efforts in the field of solar energy technologies.

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(a) How efficient are plants at converting solar energy into useable biomass energy?

(b) How efficient are solar collectors? What are the advantages and disadvantages of such systems?

(c) How efficient are photovoltaic cells? What are the advantages and disadvantages of such systems?

(d) Why is it important to factor in life expectancy and cost when judging the value of a new technological innovation?

(e) Has artificial photosynthesis been achieved?

(f) What are the possible applications of artificial photosynthetic systems? Outline the advantages they might have over non-photosynthesis-based methods.

2. As a scientific researcher, you are attending an upcoming environmental conference to discuss artificial photosynthesis. Prepare a brochure or slide presentation highlighting the possible applications of this new technology.

Stage 3: The Calvin Cycle and Carbon Fixation

The final stage of photosynthesis is carbon fixation, which is the formation of high-energy organic molecules from CO_2. This process is referred to as the Calvin cycle, in honour of Melvin Calvin, who won the 1961 Nobel Prize in Chemistry for his work in discovering this pathway. The cycle involves a large number of light-independent reactions and is presented in a simplified form in **Figure 6** on the next page.

The Calvin cycle utilizes both ATP molecules and high-energy electrons carried by NADPH from the light-dependent reactions (Stages 1 and 2) to make G3P, a sugar that is

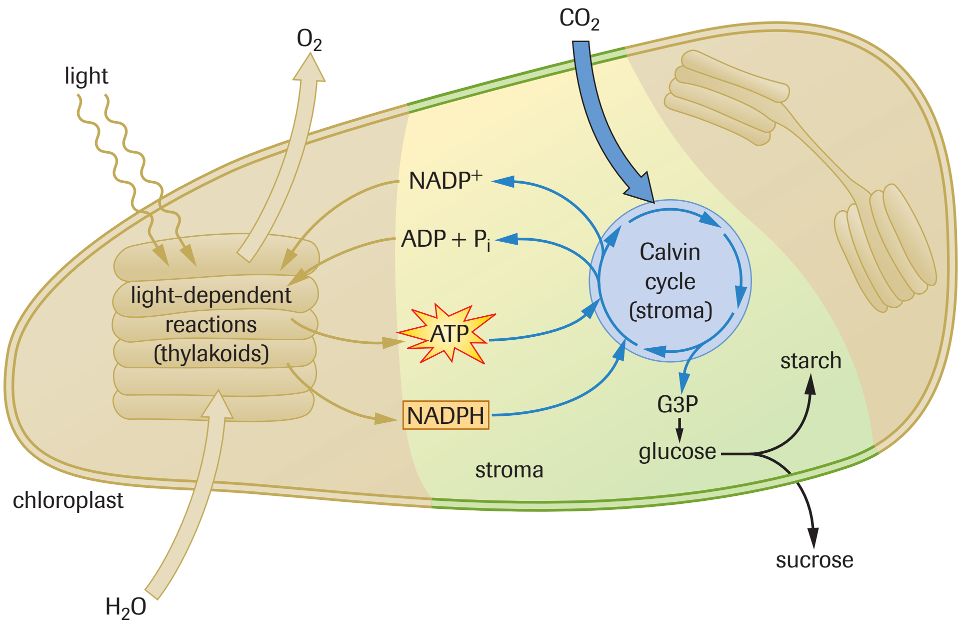

Figure 6
The Calvin cycle is the final stage of photosynthesis and takes place in the stroma. It uses NADPH and ATP to reduce CO_2 to G3P, a sugar that is used to make glucose and other carbohydrates, such as sucrose, cellulose, and starch.

used to create glucose. In these carbohydrates, the carbon and oxygen atoms are supplied by the CO_2 while the hydrogen atoms are supplied by the light-dependent reactions. Three ATPs and two NADPHs are consumed for every CO_2 that enters the cycle. Therefore, the building of even one simple sugar molecule such as glucose ($C_6H_{12}O_6$) requires the energy from 18 ATP molecules and the electrons and protons carried by 12 NADPH molecules.

Note that the amount of water produced during the Calvin cycle is less than that consumed during the light-dependent reactions. In total, there is a net consumption of six water molecules for every one glucose molecule formed.

In order for the Calvin cycle to operate within the stroma of the chloroplast, CO_2 must be readily available. In most plants CO_2 diffuses directly into the photosynthesizing plant leaf cells and chloroplasts from air spaces within the leaves. These air spaces are connected to the outside environment via tiny openings in the surface of the leaves.

DID YOU KNOW?

Benson and Bassham

Melvin Calvin did not explain carbon fixation on his own. Andrew Benson and James Bassham also made significant contributions. The Calvin cycle is therefore also called the Calvin-Benson cycle or the Calvin-Benson-Bassham (CBB) cycle.

Practice

15. Where in the chloroplast does the Calvin cycle occur?

16. Name the final product of the Calvin cycle. What happens to this compound?

INVESTIGATION 6.2 *Introduction*

How Does Carbon Dioxide Concentration Affect the Rate of Photosynthesis?

Photosynthesis involves light-dependent reactions and biochemical reactions that do not directly require solar energy. Plants live in a variety of environments on Earth. Do changes in environmental conditions affect the rate of photosynthesis? In Investigation 6.2. you will design experiments to measure the rate of photosynthesis in various conditions of light intensity, temperature, CO_2 concentration, and other factors.

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ● Prediction
- ● Design
- ○ Materials
- ● Procedure
- ● Evidence
- ● Analysis
- ● Evaluation
- ● Synthesis

To perform this investigation, turn to page 197.

WWW **WEB Activity**

Web Quest—Factors Affecting Photosynthesis

How do different variables affect photosynthesis? Is it possible to speed it up or slow it down, just by changing the colour or intensity of light? How does the CO_2 present affect photosynthesis? This Web Quest lets you design experiments in a computer simulation to find the answers to these questions and more. See if you can figure out the optimal levels of different variables for the optimal rate of photosynthesis!

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SUMMARY *The Reactions of Photosynthesis*

- The light-dependent reactions of photosynthesis take place within chloroplasts in two stages:
  - Stage 1: Both photosystems I and II capture light energy and transfer it to electrons.
  - Stage 2: The energy transferred to the electrons is used to produce a buildup of H^+ ions inside the thylakoid space, and to produce high-energy NADPH molecules.
- The light-dependent reactions consume water and form ATP, NADPH, and oxygen.
- The following events occur in chemiosmosis during Stage 2:
  - H^+ ions are pulled across the thylakoid membrane by the electron transport chain, creating an H^+ ion gradient and a buildup of positive charge within the lumen.
  - The H^+ ions leave the lumen, passing through ATP synthase complexes embedded in the thylakoid membrane.
  - The concentrated H^+ ions release energy as they escape from the thylakoid space and this energy is used to form high-energy ATP molecules.
- The Calvin cycle is Stage 3 of photosynthesis and takes place in the stroma. It uses NADPH and ATP to reduce CO_2 to G3P, which is then used to make glucose. Glucose is then made into other carbohydrates.
- Building one simple sugar molecule such as glucose ($C_6H_{12}O_6$) requires the energy from 18 ATP molecules and the electrons and protons carried by 12 NADPH molecules.

Section 6.2 Questions

1. What is ATP?

2. Write an equation to represent the overall reaction of photosynthesis.

3. (a) What is the primary function of photosynthesis?
(b) Where in the chloroplast do the light-dependent reactions occur?
(c) What are the products of the light-dependent reactions?
(d) In what phase of photosynthesis are the products of the light-dependent reactions used?

4. (a) Name the gas released as a byproduct of the light-dependent reactions of photosynthesis.
(b) Name the molecule that is the source of this gas.

5. In an experiment, a bean plant is illuminated with green light and another bean plant of similar size is illuminated with equally intense blue light. If all other conditions are controlled, how will the photosynthetic rates of the two plants most probably compare?

6. (a) How many molecules of CO_2 must enter the Calvin cycle for a plant to ultimately produce a sugar, such as sucrose, that contains 12 carbon atoms?
(b) How many ATP molecules will be used?
(c) How many NADPH molecules will be used?

7. On a sheet of blank paper, draw a labelled diagram with a single caption to teach the process of photosynthesis to a grade 4 student who has never heard of the process.

INVESTIGATION 6.1

Separating Plant Pigments from Leaves

Plants produce thousands of different chemical compounds, many of which have been found to be useful in medicine, as foods, and in industry. The first step to finding useful plant compounds is to separate the components of a plant tissue. The properties of each separate component may then be tested and the compound identified. Chromatography is a technique that separates different chemicals in a mixture based on their solubility in a particular solvent solution. In this activity, you will use paper chromatography to separate some of the different pigments found in a plant leaf.

Report Checklist

● Purpose	○ Design	● Analysis
● Problem	○ Materials	● Evaluation
○ Hypothesis	○ Procedure	○ Synthesis
● Prediction	● Evidence	

Materials

safety goggles	test-tube rack
laboratory apron	scissors
spinach leaf	pencil
chromatography solvent (acetone)	chromatography tube with cork stopper
filter paper, 12 cm long	cork stopper with a paper-clip hook
dime	

The chromatography solvent is volatile and flammable.

Use the solvent only under a fume hood.

Do not use the solvent in a room with an open flame.

Chemicals should be dispensed only by the teacher.

Wear eye protection and a laboratory apron at all times.

Procedure

1. Obtain a piece of filter paper that is long enough so the tip of the strip reaches the solvent when the strip is suspended in the test tube. Handle the paper by the edges only, to avoid transferring oil from your skin.
2. With the scissors, trim the filter paper to a point at one end. At 3 cm above the point, draw a light line in pencil across the width of the filter paper.
3. Obtain a fresh spinach leaf and place it over the pencil line on the filter paper.
4. Roll the edge of a dime across the leaf, so that the dime edge crushes the leaf tissue onto the filter paper along the pencil line.
5. Repeat step 4 several times until the pencil line has been soaked with a thin, dark band of spinach leaf extract.
6. Obtain the cork stopper with a hook formed from a paper clip. Insert the hook into the upper (straight) edge of the chromatography paper strip.
7. Obtain a chromatography tube containing 3 mL of chromatography solvent from your teacher. Keep the tube tightly stoppered and standing upright in the test tube rack.
8. Under the fume hood, remove the cork stopper that is in the chromatography tube. Replace it with the stopper to which you attached the paper strip in step 6, as shown in **Figure 1**. The tip of the paper must just touch the solvent, and the line of leaf extract must stay above the surface of the solvent. Ensure that the chromatography paper is not touching the sides of the chromatography tube. Tightly stopper the chromatography tube and carefully stand the tube upright in the test tube rack.

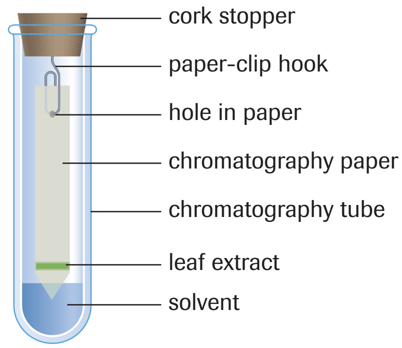

Figure 1
A chromatography setup

9. Observe the movement of solvent and extract for 15 min to 30 min. Remove the paper strip before the solvent reaches the top of the paper, and replace the stopper in the tube.
10. Still working under the fume hood, draw a pencil line across the paper strip at the uppermost point reached by the solvent before it dries and becomes invisible. Also mark each pigment band and record its colour before it fades. Keep the paper strip under the fume hood until it is completely dry.

INVESTIGATION 6.1 *continued*

(a) At your desk, measure and record the distance from the original pencil line to the middle of each pigment band. Also measure and record the distance the solvent travelled from the pencil line.

Analysis

(b) After chromatography, compounds may be identified from their R_f values. These values compare the distance travelled by a compound with the distance travelled by the solvent. Calculate the R_f values for each compound on your filter paper according to the following equation:

$$R_f = \frac{\text{distance travelled by compound}}{\text{distance travelled by solvent}}$$

(c) How many compounds were you able to separate using chromatography?

(d) Draw a life-sized diagram of your chromatography strip, showing the precise locations of the pigments and solvent solution.

Evaluation

(e) The more soluble a compound is in a solvent, the farther it will travel during chromatography. **Table 1** gives some properties of pigments commonly found in plant leaves. Which pigments were in your leaf extract? Explain your answer.

Table 1 Common Leaf Pigments

Pigment	Colour	Relative solubility in acetone
chlorophyll *a*	bright green to blue-green	medium
chlorophyll *b*	yellow-green to olive green	medium–low
carotenes	dull yellow-orange	high
xanthophylls	bright yellow to orange	medium–high

(f) List the R_f values for the pigments you identified in the preceding question. Describe the relationship between R_f value and solubility.

(g) Compare your R_f values to those recorded by the other groups in your class. Were the R_f values for each pigment always the same? How might this affect the use of R_f values to identify chemical compounds?

(h) Suggest a step that could be added to the procedure to isolate a specific compound for chemical testing.

Extension

(i) Obtain a black water-soluble marker. Repeat steps 1 to 3, but replace the solvent with water and use the marker to draw a line across a piece of filter paper in step 3. Allow the ink to dry and then draw another line on top of the first. Repeat this several times until you have a very dark ink line across the paper. Perform a chromatography as in this activity. Report your findings to the class.

(j) The colourful Haida mask in **Figure 2** may have been dyed using pigments obtained from local plants. Brainstorm methods the Haida people might use to extract these pigments from leaves, roots, and stems.

Figure 2
Haida mask

EXTENSION

Chromatography
In this Virtual Biology Lab, you can use TLC (thin-layer chromatography) to separate and analyze the pigments in a spinach leaf extract.

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INVESTIGATION 6.2

Report Checklist

○ Purpose	● Design	● Analysis
○ Problem	○ Materials	● Evaluation
○ Hypothesis	● Procedure	● Synthesis
● Prediction	● Evidence	

How Does Carbon Dioxide Concentration Affect the Rate of Photosynthesis?

Photosynthesis involves light-dependent reactions and biochemical reactions that do not directly require light. Plants live in a variety of environments on Earth. Do changes in environmental conditions affect the rate of photosynthesis? In this investigation, you will measure the rate of photosynthesis in various conditions by quantifying the amount of oxygen being released from a photosynthesizing solution.

Problems

1. How do changes in light intensity, temperature, and CO_2 concentration affect the rate of photosynthesis?
2. Develop your own question regarding the effect of an environmental condition of your choice on the rate of photosynthesis.

Predictions

(a) Predict the effect that changes in each of the following environmental conditions will have on the rate of photosynthesis:
  (i) light intensity
  (ii) temperature
  (iii) CO_2 concentration
  (iv) another environmental condition of your choice

Design

The procedure outlined in this investigation provides a method for measuring the rate of photosynthesis of plants submersed in an aqueous sodium bicarbonate buffer (pH 7). Sodium bicarbonate is used as a source of $CO_2(aq)$. You will use this procedure to measure the rate of photosynthesis in four experiments that you will design and perform. In each case, you must conduct controlled experiments that allow you to make reasonable comparisons.

(b) Design three experimental procedures to determine
  (i) the effect of varying light intensity on the rate of photosynthesis
  (ii) the effect of varying temperature on the rate of photosynthesis
  (iii) the effect of varying concentration of dissolved carbon dioxide on the rate of photosynthesis

Have your teacher approve each experimental procedure, then carry out the experiments. Use the procedure outlined in this investigation to measure the rate of photosynthesis in each case. Record all observations and measurements in a suitable table format.

(c) Design an experimental procedure to test the prediction you made in (a) (iv). Obtain teacher approval, then carry out the experiment. Record all observations and measurements in suitable table format.

Materials

safety goggles
laboratory apron
500 mL conical flask or large test tube
plants (terrestrial plants or water plants)
sodium bicarbonate buffer, pH 7
rubber stopper with glass tubing
rubber tubing
50 mL burette
distilled water
500 mL beaker
utility stand and clamp
rubber bulb
ice
sodium bicarbonate
thermometer
light intensity meter
other materials and equipment as necessary
200 W light bulb

Procedure

1. Put on your safety goggles and lab apron.
2. Fill the 500 mL conical flask with plant material.
3. Add enough sodium bicarbonate buffer to submerse the plant material.
4. Put the stopper with glass tubing onto the mouth of the conical flask. Make sure that the glass tubing does not touch the contents of the flask.
5. Place 400 mL of water into a 500 mL beaker. Fill the burette with water to the top, then invert it in the beaker and secure it with a clamp to the utility stand (**Figure 1**, next page).
6. Use rubber tubing to connect the open end of the glass top in the stopper of the flask to the bottom of the burette. The rubber tubing needs to be air tight within the glass tubing, but should fit loosely in the bottom of the burette. Be sure there is space for the water to escape when the gas bubbles up the burette.

INVESTIGATION 6.2 *continued*

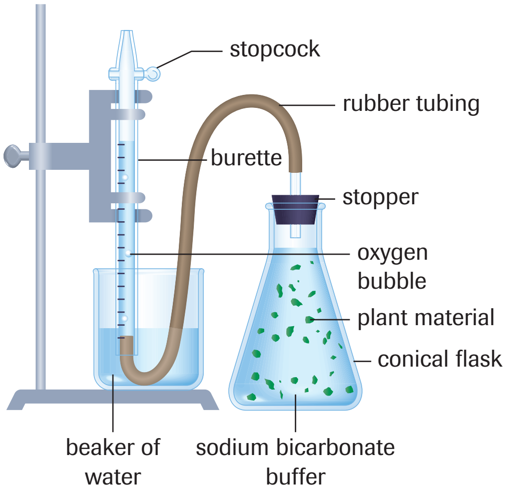

Figure 1
Gas collection apparatus setup

7. Open the burette stopcock carefully and allow the water level to drop to the 50 mL level on the burette.
8. Subject the system to conditions according to your design. Allow several minutes for the system to stabilize.
9. Follow the rate of photosynthesis by either counting the number of bubbles over 1 min spans or measuring the amount of water displaced over 5 min spans. Measure for a total of 10 min for each condition. If you get no bubbles, check if the meniscus in the tubing is moving. If it is, then your burette valve is leaking. Your teacher will help you correct this problem.

Analysis

(d) In tables, summarize the results for the variables you tested. Draw suitable graphs using your data.

(e) Analyze your results for trends and patterns. Answer the Questions.

(f) Compare your results with those of the rest of the class.

Evaluation

(g) In your report, evaluate your predictions, taking into account possible sources of error. Draw reasonable conclusions.

(h) Describe how you could improve your experimental methods and the assay technique.

(i) Suggest other experiments you could perform to extend your knowledge of photosynthetic activity.

(j) The experiments you conducted in this investigation were carried out with plants submerged in water. Design a procedure for carrying out the same types of experiments in air instead of water. Draw a labelled diagram, like **Figure 1**, to illustrate your experimental design.

(k) What environmental conditions affecting the rate of photosynthesis can be tested in an air environment that could not be tested in a water environment?

Synthesis

(l) Suggest a procedure you might use to identify the type of gas produced by the plant material in these experiments.

EXTENSION

Carbon Dioxide Fixation

You can confirm the results of the experiment you designed or carry out additional experiments on factors that affect the rate of photosynthesis in the Virtual Biology Lab.

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Chapter 6 SUMMARY

Outcomes

Knowledge

- explain, in general terms, how pigments absorb light and transfer that energy as reducing power in $NADP^+$, NADPH, and finally into chemical potential in ATP by chemiosmosis, describing where those processes occur in the chloroplast (6.1, 6.2)
- explain, in general terms, how the products of the light-dependent reactions, NADPH and ATP, are used to reduce carbon in the light-independent reactions for the production of glucose, describing where the process occurs in the chloroplast (6.2)

STS

- explain how scientific knowledge may lead to the development of new technologies and new technologies may lead to scientific discovery (6.2)
- explain that the appropriateness, risks, and benefits of technologies need to be assessed for each potential application from a variety of perspectives, including sustainability (6.2)

Skills

- ask questions and plan investigations (6.1, 6.2)
- conduct investigations and gather and record data and information (6.1, 6.2)
- analyze data and apply mathematical and conceptual models by: collecting and interpreting data and calculating R_f (reference flow) values from chromatography experiments (6.1); and drawing analogies between the storage of energy by photosynthesis and the storage of energy by active solar generating systems (6.2)
- work as members of a team and apply the skills and conventions of science (all)

Key Terms

6.1

photon
chlorophyll
chloroplast
stroma
thylakoid
grana
lamellae
thylakoid membrane
thylakoid lumen

6.2

ATP
ADP
$NADP^+$
NADPH
light-dependent reactions
carbon fixation
Calvin cycle
light-independent reactions
photosystem
electron transport chain
photolysis
oxidation
reduction
ATP synthase complex
chemiosmosis

MAKE a summary

1. Using a large piece of paper, draw a poster summarizing the three stages of photosynthesis. The paper represents the cytoplasm of a plant cell. Draw a chloroplast covering at least half ot the paper. Place different drawings representing each stage of the process in the appropriate locations.
2. Revisit your answers to the Starting Points questions at the start of the chapter. Would you answer the questions differently now? Why?

Go To

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The following components are available on the Nelson Web site. Follow the links for *Nelson Biology Alberta 20–30*.

- an interactive Self Quiz for Chapter 6
- additional Diploma Exam-style Review Questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in the chapter.

EXTENSION

CBC radio ONE QUIRKS & QUARKS

Low Light Life
Dr. Tom Beatty, (a microbiologist from the University of British Columbia) and his team have discovered photosynthetic bacteria in the deep-sea oases formed around hydrothermal vents. This bacteria uses the light generated by infrared energy from the hot environment and stray photons produced by chemical reactions.

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Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix A5. Science Directing Words used in Diploma Exams are in bold type. Exam study tips and test-taking suggestions are on the Nelson Web site.

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DO NOT WRITE IN THIS TEXTBOOK.

Part 1

1. The raw materials for photosynthesis are
A. oxygen and water
B. carbon dioxide and water
C. glucose and oxygen
D. oxygen and carbon dioxide

2. The word equation that summarizes photosynthesis is
A. water + starch → glucose + glucose + glucose
B. water + carbon dioxide → oxygen + glucose
C. glucose + oxygen → water + carbon dioxide
D. carbon dioxide + glucose → water + oxygen

Use the following information to answer questions 3 and 4.

Figure 1 shows events taking place inside the chloroplast during photosynthesis. The tan region is the stoma and the green region is the thylakoid lumen. These regions are separated by the thylakoid membrane.

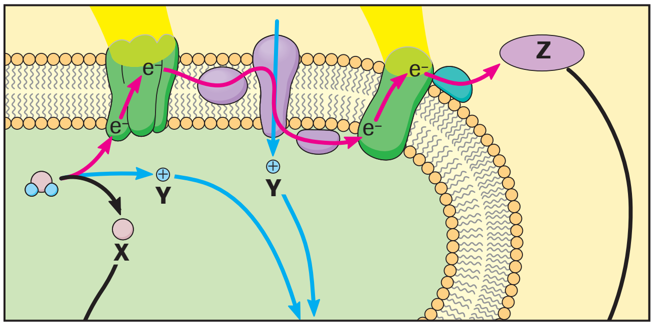

Figure 1

3. The letters X, Y, and Z represent
A. water (X), NADPH (Y), H^+ (Z)
B. chlorophyll (X), oxygen (Y), ATP (Z)
C. NADPH (X), H^+ (Y), water (Z)
D. oxygen (X), H^+ (Y), NADPH (Z)

4. The function of the electron transport chain in this pathway is to
A. energize electrons for the reduction of $NADP^+$
B. pump H^+ ions out of the lumen to generate ATP
C. move electrons from photosystem I to photosystem II
D. produce oxygen

5. The process of splitting water to release hydrogen ions, electrons, and oxygen occurs
A. during the light-dependent reactions
B. during the Calvin cycle
C. during photorespiration
D. during carbon fixation

6. The process of incorporating the carbon of carbon dioxide into carbohydrates occurs
A. during the light-dependent reactions
B. during the Calvin cycle
C. during carbon fixation
D. during B and C

Use the following information to answer questions 7 and 8.

The herbicide 3-(3,4-dichlorophenyl)-1,1 –dimethylurea (DSMU) blocks the transfer of electrons from photosystem II into the electron transport chain.

7. This herbicide would effect ATP and glucose production in the following ways:
A. increase ATP production; decrease glucose production
B. decrease ATP production; increase glucose production
C. stop ATP production; stop glucose production
D. decrease ATP production; stop glucose production

8. The herbicide will kill the plant because it will
A. stop the production of glucose and other carbohydrates
B. stop the production of ATP
C. stop the production of oxygen gas
D. stop the pumping of H^+ ions across the thylakoid membrane

9. NR The following data were collected from several different chromatography experiments using the same solvent. Calculate the R_f values for each of the pigments and then place these values in order from most soluble to least soluble. (Record all four digits of your answer, rounded to two decimal places.)

Pigment	A	B	C	D
Solvent distance travelled	12.1 mm	6.0 mm	8.4 mm	9.5 mm
Pigment distance travelled	5.8 mm	2.2 mm	8.1 mm	1.4 mm

10. NR Place the following molecules in the order that they first appear directly in the chemical pathways of photosynthesis. (Record all four digits of your answer.)
1. CO_2
2. glucose
3. oxygen
4. water

Part 2

11. (a) **Determine** which has more energy: short wavelengths or long wavelengths of electromagnetic radiation.
(b) **Identify** the range of wavelengths plants use in photosynthesis.

12. Some old biology textbooks called the carbon fixation reactions of photosynthesis the "dark reactions."
(a) **Why** did they use this term?
(b) **Why** is this misleading?

Use the following information to answer questions 13 to 18.

The data in **Table 1** were obtained by extracting the pigments from spinach leaves and placing them in an instrument called a spectrophotometer that measures the amount of light (of different wavelengths) absorbed by pigments.

Table 1 Absorption Spectrum of Spinach Leaf Pigments

Wavelength (nm)	Absorbance (%)	Wavelength (nm)	Absorbance (%)
400	0.42	560	0.12
420	0.68	580	0.15
440	0.60	600	0.17
460	0.58	620	0.25
480	0.83	640	0.40
500	0.23	660	0.32
520	0.11	670	0.56
540	0.12	680	0.24

13. DE **Sketch** a line graph of the data with percent absorbance along the vertical axis and wavelength along the horizontal axis. Indicate the colours of the visible spectrum corresponding to the wavelengths along the horizontal axis.

14. DE **Identify** the colours of an intact spinach leaf that would be least visible. Explain.

15. DE **Identify** the colour that is least absorbed by the pigment extract. Explain.

16. DE **Compare** this graph to the absorption spectrum in **Figure 3** on page 182. Identify the pigment most likely responsible for the peak at 670 nm.

17. DE **Why** are there no peaks in the range of 500 nm to 620 nm?

18. DE **Identify** the pigments primarily responsible for absorption in the range of 400 nm to 480 nm.

Use the following information to answer questions 19 to 21.

A research scientist is able to remove and isolate chloroplasts from plant cells. She places them in an acidic solution of pH 4 (having a very high H^+ concentration) and waits until both the stroma and inner thylakoid space reach this same pH level. She then removes the chloroplasts and places them in a solution of pH 8 in the dark. She notices that the chloroplasts begin synthesizing ATP.

19. DE **Explain** the scientist's observations.

20. DE **Why** did she choose to perform the experiment in the dark rather than the light?

21. DE **Describe** the expected result if she had tested for the presence of products from the Calvin cycle? Explain.

Use the following information to answer questions 22 to 24.

Supplies of fossil fuels are limited, and concerns over increasing atmospheric CO_2 levels are providing an incentive to make better use of solar energy. In the future, photosynthetic organisms may be used to harness solar energy to produce clean-burning fuels, such as ethanol or hydrogen gas. Researchers have already had some success getting certain algae to produce hydrogen gas from water using photosystem II, while others are attempting to harness photosynthesis processes to produce methane gas (CH_4).

22. DE **Describe** the advantages of hydrogen gas as a fuel compared to methane.

23. DE Considering all of the products of photosynthesis, **describe** a safety problem that might arise if either of these fuels were being produced in large quantities by photosynthetic processes.

24. DE If photosynthesis were used as a source of methane gas, **conclude** whether burning methane as a fuel would have any influence on atmospheric CO_2 levels. **Explain** your conclusion.

25. Biomass is plant matter such as trees, grasses, and agricultural crops. Conduct research on using biomass as a fuel source (biofuel). Then, write a unified response addressing the following aspects of using biofuel.
- **Describe** how electricity is generated from biofuel.
- **Determine** what proportion of electric power production in Canada comes from biomass energy. **Summarize** the potential for increasing the amount of electricity produced by biomass.
- **Compare** the costs and benefits of producing automobile fuel from biomass with those of producing fuel from petroleum.

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